Limits on Planets Orbiting Massive Stars from Radio Pulsar Timing

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Abstract

When a massive star collapses to a neutron star, rapidly losing over half its mass in a symmetric supernova explosion, any planets orbiting the star will be unbound. However, to explain the observed space velocity and binary fraction of radio pulsars, an asymmetric kick must be given to the neutron star at birth. Occasionally, this kick will prevent the resulting pulsar-planet system from unbinding. We estimate the survival probability of a Jupiter-type planet in an asymmetric supernova explosion, and show that if a typical massive star has one such planet then several known non-millisecond pulsars should possess planetary companions. Conversely, if pulsar timing measurements fail to detect planets orbiting these pulsars, then the average number of such planets per star is less than about 0.5.

Subject headings: pulsars - planetary systems -- supernovae

1 Introduction

The discovery of two planets orbiting the millisecond pulsar PSR B1257+12 (Wolszczan and Frail 1992) suggests both that planets may be relatively easy to form and that searches for planets orbiting unusual hosts may be profitable. Very little is known, for example, about planets orbiting massive main sequence (O and B) stars. In part this is due to astronomers' prejudices in favor of the F, G, K, and M stars that might host Earth-like planets, but it is also because the search for planets orbiting massive stars poses enormous technical problems. For example, a Jupiter-mass planet at 5 AU distance from an S $M_{\odot}$ star induces radial velocity variations in the primary smaller than 5 km s^{-1}, far below current limits given the small number of shallow spectral lines available for precise spectroscopy of B stars.

The poor spectroscopy possible for B stars contrasts dramatically with the extremely good "spectroscopy" possible for their evolutionary descendants, the radio pulsars. In the best case, timing experiments could easily detect the Earth orbiting a millisecond pulsar (Thorsett and Phillips 1992), and even the simplest observations could readily detect Jupiter orbiting nearly any known radio pulsar (Thorsett, Phillips, and Cordes 1993).

By estimating the fraction of planets that survive the supernova explosion that accompanies pulsar formation and setting limits on the fraction of radio pulsars that have planetary companions, we can limit the average number of planets that originally orbited the progenitor stars. In § 2, we argue that massive planets are likely to survive the explosion intact, and show that the a-symmetric supernova explosions that are required to explain observed pulsar velocities and binary fractions also predict a small but significant probability that a planet will remain bound to the pulsar. In § 3, we review the available limits on planets orbiting pulsars. In § 4, we discuss the implications of these calculations for the search for planets orbiting radio pulsars, and show how timing observations will eventually lead to interesting limits on the average number of planets orbiting massive stars.

2 Planet Survival

We are interested in the probability that a planet orbiting the progenitor of a radio pulsar will survive to orbit the pulsar. Neutron stars are formed in the Type II supernova explosions of massive stars. The lower mass cutoff for neutron star formation is somewhat uncertain. The problem has been briefly reviewed by Bhattacharya (1991). Most calculations suggest the mass limit is about $8M_\odot$, though non-standard convective overshoot assumptions can reduce this to about $6.5\,M_\odot$. Observational attempts to match local star counts to the local pulsar birth rate suggest a limit between 6 and $8M_\odot$. Main sequence masses may be slightly reduced by mass loss due to stellar winds before collapse. Because of the steep initial mass function, most pulsars will be descended from stars near the lower mass limit. For simplicity, we therefore assume an $8M_\odot$ progenitor and a $1.4M_\odot$ neutron star.

Several hazards face a planet orbiting a massive star. A planet may spiral into the supergiant envelope of the evolving star or be destroyed by supernova ejects when it collapses. If the planet survives stellar evolution intact, the sudden decrease in the stellar mass may unbind the system. Finally, the planet must avoid vaporization by the pulsar wind. We examine each factor in turn.

Rees, Trimble, and Cohen (1971) have argued that a planet can survive the direct heating of a supergiant envelope that surrounds it (though its atmosphere will be evaporated), but point out that if it sweeps up material comparable to its own mass it will spiral into the star.

This occurs within a few thousand years, much less than the envelope lifetime for the $\sim 8M_\odot$ stars which we are considering. We will therefore assume that all planets with orbits within the giant envelope will be destroyed. The outer radius of the giant envelope is somewhat uncertain, but is probably less than 3 AU (Weaver, Zimmerman, and Woosley 197 S).

Any planets that survive the supergiant stage are also likely to survive the supernova explosion intact, as they intercept too small a fraction of the ejects to be shock evaporated (Colgate 1970; Bailes, Lyne, and Shemar 1991). They are, however, very likely to be ejected from the system. In the explosion, the kinetic energy of each planet is unchanged (the contribution from the intercepted ejects is negligible), but the potential energy is reduced by an amount Am/r-rz$_0$ where m_0 and Δm are the initial system mass and the mass of the supernova ejects. If $\Delta m > \frac{1}{2}m_0$ in a symmetric explosion, then planets in initially circular orbits will be lost into hyperbolic orbits (Blaauw 1961).

There is strong evidence, however, from observations of neutron star binaries, as well as from the statistics of the pulsar population as a whole, that the supernova explosions in which pulsars are born are not symmetric. Burrows and Woosley (1986) argue that the neutron star companion of the binary pulsar PSR B1913+16 must have received a $\sim$ 100 km s^{-1} velocity kick in the orbital plane at birth to explain the current binary parameters. Even stronger evidence is provided by the low eccentricity of PSR B1534+12; this a neutron star binary, similar to PSR B1913+16, with an eccentricity of 0.27, a pulsar mass of $1.32M_\odot$ and companion mass $1.36M_\odot$ (Wolszczan 1991). The progenitor of PSR B1534+12 is believed to have been a close binary system which underwent significant mass transfer/loss during the evolution of both the primary and the secondary, leaving the He core and neutron star in a tight circular orbit just prior to the formation of the second neutron star. To produce the observed eccentricity with a symmetric explosion, the mass of the He core must have been $\lesssim 2.1M_\odot$. It is very unlikely that a helium star this small could explode and leave a neutron star with a gravitational mass $\gtrsim 1.32M_\odot$ (Woosley 1987; van den Heuvel 1987). In both the PSR B1913+16 and PSR B1534+12 binary systems, there is evidence for misalignment between the pulsar spin and orbital angular momenta, indicative of a velocity kick perpendicular to the orbital plane during the second supernova explosion (Weisberg, Romani, and Taylor 1989, and J. A. Phillips, private communication). Most generally, Dewey and Cordes (1987) show that the velocity distribution and binary fraction of observed pulsars is inconsistent with symmetric supernova explosions. They perform monte carlo simulations of radio pulsar evolution, with and without velocity kicks and with various assumptions about the distribution of primordial binaries. They find that models without kicks produce either too many low velocity pulsars ('for low initial binary fraction), or too many binary pulsars (for high initial fraction). Their best fit to the observed data comes from a model which includes a Maxwellian distribution of velocity kicks with $\langle v \rangle$ = 90km s-' .

Hills (1983) has developed analytical expressions for binary evolution with arbitrary velocity kicks. If the neutron star receives a velocity kick Δv in a direction θ relative to pre-explosion orbital velocity of its progenitor, and in the pre-explosion system the relative velocity between the progenitor and the planet is v_0, then, for a planet of $m_p << m_0$ in a circular orbit, ejection occurs if

$$\theta < \theta_c = \cos^{-1}\left[\frac{1 - 2(\Delta m/m_0) - (\Delta v/v_0)^2}{2(\Delta v/v_0)}\right]$$

(Hills 1983). If the square bracketed expression is less than – 1 the planet is ejected regardless of θ; if it is greater than +1 the planet is never ejected. Between those limits the probability that the planet is retained (for a random θ) is

$$p = \frac{1}{2}\left\{1 + \left[\frac{1 - 2(\Delta m/m_0) - (\Delta v/v_0)^2}{2(\Delta v/v_0)}\right]\right\}. \tag{1}$$

Figure 1, shows the probability (as a function of kick velocity and original orbital size) that a planet is retained when an $8M_\odot$ start explodes leaving a $1.4M_\odot$ remnant.

In general, the post-supernova orbits of the retained planets are highly eccentric, and wider than the those of the pre-explosion systems. For example. monte carlo simulations of a planet in a circular, 5 AU (4 yr) orbit around an $8M_\odot$ star that collapses to a $1.4M_\odot$ neutron star, show that the planets that remain bound have a median eccentricity e = 0.76 and period P = 17 yrs.

Even after surviving the supernova explosion in bound orbits. these planets face one last hurdle: avoiding evaporation by high energy pulsar radiation. This problem has been considered by Rees *et al.* (1971), whose results suggest that even the Crab. with luminosity $L \sim 10^{38}$ erg s-', is unlikely to evaporate even the closest remaining planets in less than $\sim 10^5$ yrs, by which time its luminosity will be several orders of magnitude lower. Hence planets which survive the red giant phase, and remain bound through the supernova explosion, are permanent.

In summary, the probability that a planet whose original orbit is outside the red giant envelope of its evolving host star will remain bound as a planet orbiting the descendent radio pulsar depends only on the probability S that it remains bound during the supernova event. We can estimate S by integrating eqn. 1 over the distribution of kick velocities. For $m_0 = 8M_\odot$ and a Maxwellian velocity distribution with (v) = 90 km s^{-1}, we find that for 3, 5, and 10 AU orbits S is 2.9%, 1.6%, and 0.7%, respectively.

3 Pulsar Timing and Planetary Systems

There are two planets known to be orbiting the millisecond pulsar PSR B1257+12 (Wolszczan and Frail 1992), and evidence for a planet orbiting the binary millisecond pulsar system PSR B1620−26, in the globular cluster M4 (Backer 1993; Thorsett, Arzoumanian, and Taylor 1993). PSR B1257+12 has been spun-up through mass transfer from a binary companion that is no longer present; the planets were probably not formed orbiting the massive star that became the pulsar, but were rather from a disk left after the evaporation or violent destruction of the companion (Podsiadlowski 1993; Phinney and Hansen 1993). The genesis of a putative planet orbiting PSR B1620−26 is less clear: it might be primordial, formed orbiting a binary system, or it might have been captured together with its original host star in an exchange collision (Sigurdsson 1993). A planet was recently reported orbiting the pulsar PSR B1829–10, but the signal was found to be an artifact of the data processing (Bailes, Lyne, and Shemar 1991; Lyne and Bailes 1992). As yet, no convincing evidence for a planetary mass body orbiting a normal (non-millisecond) pulsar has been found.

The use of pulsar timing data to detect or limit planetary systems orbiting pulsars has been discussed by many authors (Michel 1970; Treves 1971; Lamb and Lamb 1976; Thorsett and Phillips 1992; Bailes, Lyne, and Shemar 1993; Cordes 1993). The reflex orbital motion of the pulsar will produce periodic variations in the observed pulse phase; these are sinusoidal if the orbit is circular, more complex if it is eccentric. If the data span is longer than the orbital period these can be easily detected for most plausible planet masses and orbital parameters. A Jupiter mass planet in a ten year orbit will induce a ~ 2 s arrival time variation, while the pulsar phase can usually be measured to a few milliseconds or better. Hence a planet a thousand times smaller than Jupiter could be detected with an adequate data span. However, as noted above, a significant fraction of surviving planets are likely have orbital periods longer than 10 years, and since relatively few pulsars have been carefully timed over more than a decade, these long periods hamper detection. We have carefully studied the 23 pulsars observed by Downs and Reichley (1983), finding that none of them has a Jupiter mass planet in a circular orbit with period smaller than ~ 25 years (Thorsett, Phillips, and Cordes 1993), but setting much poorer limits on elliptical orbits. Bailes, Lyne, and Shemar (1993) have reported preliminary analysis of timing data from more than 200 pulsars observed at Jodrell Bank, but have not yet summarized their results in a way useful for determining limits on planetary systems. They do, however, conclude that planets more massive than Jupiter cannot exist orbiting more than about 10% of the pulsar population. For the last four years, regular timing observations have been made of nearly all known pulsars, by a number of groups, in support of the Compton Gamma Ray Observatory. These observations will eventually be a significant source of planetary system limits or detections.

4 Discussion

There are few theoretical predictions regarding planet formation around massive stars. The most detailed work is by Nakano (1987,1988), who argues that planets can form only in a region of orbits bounded outside by the stellar evolutionary timescale and inside by the nebular temperature. He finds that stars of mass greater than $10M_\odot$ cannot form planets at all, while $8M_\odot$ stars form planets only between about 3 and 10 AU. Objections to Nakano's conclusions, especially his outer formation limits, have been summarized by Lissauer (1989), who emphasizes the theoretical uncertainty in planet formation timescales, and the unknown dependence of disk mass, temperature structure, and angular momentum on stellar mass. In any case, there seems to be no fundamental reason planets *cannot* form around 5 AU from an $8M_\odot$ star, so it is up to the observers to determine if they are present.

Unfortunately, direct searches for these planets are very hard, because of the large luminosity of the central star and the small velocities induced on it by the low mass planet. We are aware of no significant observational constraints on planets orbiting B or O stars. However. as we have discussed, planetary systems are easily detected around their evolutionary descendants, the radio pulsars. With an estimate of the planet survival probability, observations of pulsars can be used to draw conclusions about the number of planets orbiting massive stars.

In our analysis planet survival assumed an isolated central star. Planets may also form around B stars in binaries wide enough ($\gtrsim$ 100 AU) that a protoplanetary disk can form around one component, or hierarchically from a disk around a very tight binary. (Recent observations suggest the formation of just such a disk around a T Tauri system (Mathieu *et al.* 1993).) However, the formation probability of such systems is unknown. and the problem of planet retention during a supernova in a binary system is complex and lies beyond the scope of this *Letter*. We can set a lower limit on planet formation by neglecting the possibility that any are formed in binaries. Then. in order to calculate the fraction of pulsars likely to have planet-sized companions, we need to know f_s, the fraction of observable radio pulsars descended from isolated stars. The observed fraction of B stars without companions is 49%, but due to selection effects the true fraction is considerably lower (Abt 1983). We use the assumption of model C in Dewey and Cordes (1987), that only 16.5% of B stars are single. According to their monte carlo simulations, these stars produce 24% of observable radio pulsars. We therefore assume, we believe conservatively, that $f_s \approx 0.24$.

The fraction of pulsars with planets will be

$$N_p/N = f_s S n = 3.6 \times 10^{-3} \left(\frac{f_s}{0.24}\right) \left(\frac{S}{1.5\%}\right) n$$

where n is the average number of planets formed around their massive progenitors. Thus if a typical massive star has one planet between about 3 and 7 AU, then of the $\sim$ 600 known (non-millisecond) pulsars, we expect ~ 2 to have retained their planets. It is therefore not surprising that the current searches for planets around pulsars (§ 3) have not yet been successful. However, if a careful study of the known radio pulsars fails to detect any planetary companions, then we can conclude that the average number of planets formed in this region around an isolated B stars is fewer than n $\sim$ 0.5. With many large-area pulsar surveys currently underway, the number of known pulsars is expected to increase substantially, yielding new opportunities to discover pulsar-planetary systems.

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REFERENCES

Abt, H. A. 1983, *Ann. Rev. Astr. Ap.*, 21, 343.

Backer, D. C. 1993, in *Planets around Pulsars, eel.* J. A. Phillips. S. E. Thorsett, and S. R. Kulkarni, Astron. Sot. Pac. Conf. Ser. Vol. 36, 11.

Bailes, M., Lyne, A. G.. and Shemar, S. L. 1991, *Nature*, 352.311.

Bailes, M.. Lyne, A. G., and Shemar, S. L. 1993, in *Planets around Pulsars. ed.* J. .4. Phillips, S. E. Thorsett, and S. R. Kulkarni, Astron. Sot. Pac. Conf. Ser. Vol. 36, 19.

Bhattacharya, D. 1991, in *Neutron Stars: Theory and observation, eel.* J. Ventura and D. Pines. (Dordrecht: Kluwer), 103.

Blaauw, A. 1961, *Bull. Astron. Inst. Neth.*, 15, 265.

Burrows. A. and Woosley, S. E. 19S6, *ApJ*, 30S, 6S0.

Colgate, S. A. 1970, *Nature, 225, 247*

Cordes, J. M. 1993, in *Planets around Pulsars*, ed. J. A. Phillips, S. E. Thorsett, and S. R. Kulkarni, Astron. Sot. Pac. Conf. Ser. Vol. 36, 43.

Dewey, R. J. and Cordes, J. M. 1987, *ApJ*, :321, 7S0.

Wolszczan, A. 1991, *Nature, 350, 688.*

Wolszczan, A. and Frail, D. A. 1992, *Nature, 355,* 145.

Woosley, S. E. 1987, in *The Origin and Evolution of Neutron Stars, IA U Symposium 125,* ed. D. J. Helfand and J.-H. Huang, (Dordrecht: Reidel), 255.

Figure Caption

Figure 1: The probability of planet retention for a randomly oriented kick as a function of kick velocity for three pre-explosion orbital radii.

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Downs, G. S. and Reichley, P. E. 1983, *Astrophys. J. Supp. Series*, .53, 169.

Hills, J. G. 1983, *ApJ*, 267, 322.

Lamb, D. Q. and Lamb, F. K. 1976, *ApJ*, *204, 168.*

Lissauer, J. J. 1989, in *The Formation and Evolution of Planetary Systems*, ed. H. A. Weaver and L. Danly, Cambridge, 304.

Lyne, A. G. and Bailes, M. 1992, *Nature*, 355, 213.

Mathieu, R. D., Adams. ??., Fuller, G., Jensen, E., Koerner, D. W., and Sargent, A. I. 1993, preprint.

Michel, F. C. 1970, ApJ, 159, L25.

Nakano, T. 1987, *MNRAS*, 224, 107.

Nakano, T. 1988, *MNRAS*, 230, 551.

Phinney, E. S. and Hansen, B. M. S. 1993, in *Planets around Pulsars*, ed. J. A. Phillips, S. E. Thorsett, and S. R. Kulkarni, Astron. Sot. Pac. Conf. Ser. Vol. 36, 371.

Podsiadlowski, P. 1993, in *Planets around Pulsars*, ed. J. A. Phillips, S. E. Thorsett, and S. R. Kulkarni, Astron. Sot. Pac. Conf. Ser. Vol. 36, 149.

Rees, M. J., Trimble, V. L., and Cohen, J. M. 1971, *Nature*, 229, *395*.

Sigurdsson, S. 1993, preprint.

Thorsett, S. E., Arzoumanian, Z., and Taylor, J. H. 1993, *ApJ*, *412*, L33.

Thorsett, S, E. and Phillips, J. A. 1992, *ApJ*, 387, L69.

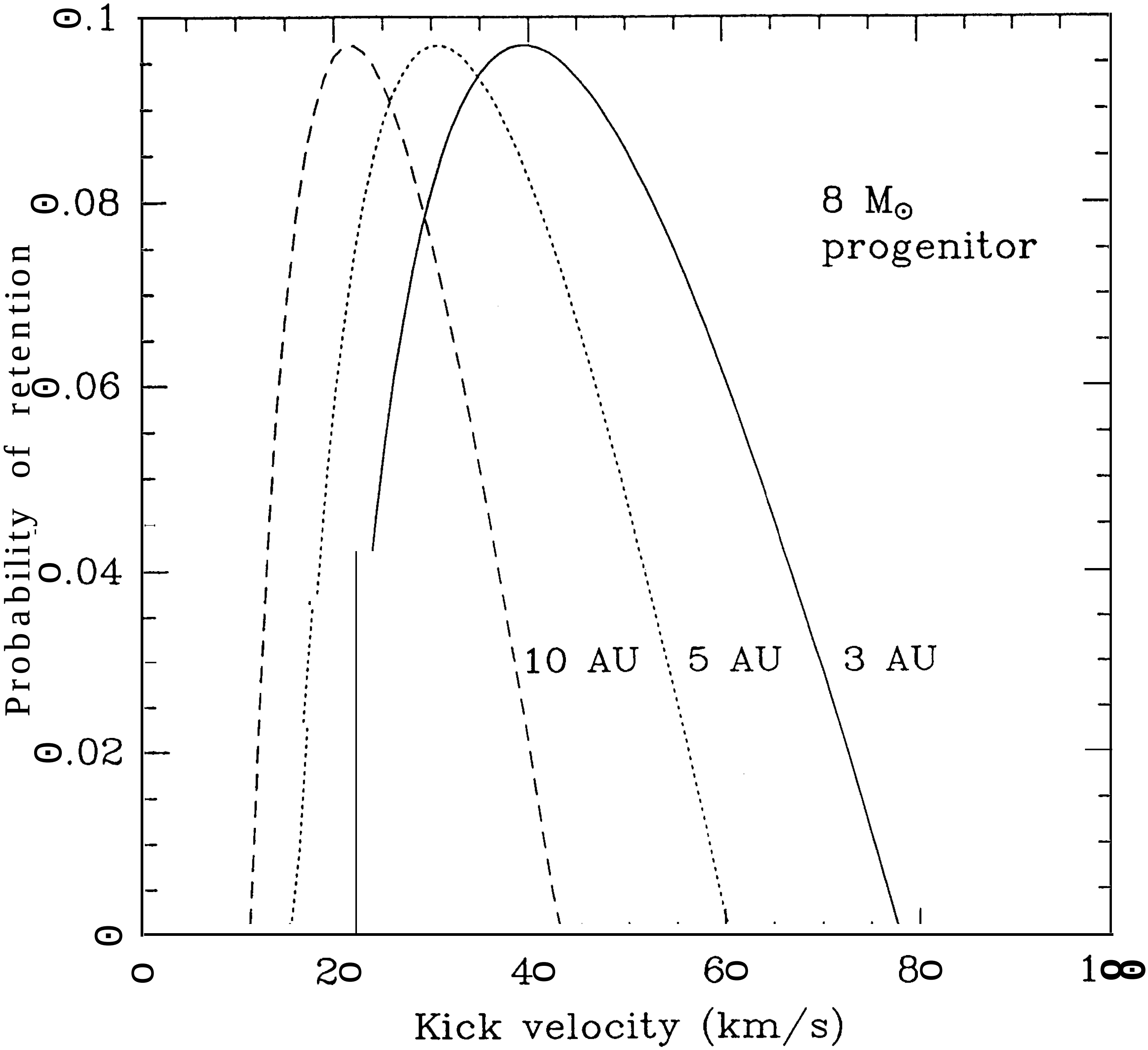
Thorsett, S. E.. Phillips, J. A.. and Cordes, J. M. 1993, in *Planets around Pulsars*, ed. J. A. Phillips, S. E. Thorsett, and S. R. Kulkarni, Astron. Sot. Pac. Conf. Ser. Vol. 36, 31.

Treves, A. 1971, *A&A*, 1.5.471.

van den Heuvel, E. P. J. 1987, in *The Origin and Evolution of Neutron Stars, IA U Symposium no. 125*, ed. D. J. Helfand and J.-H Huang, (Dordrecht: Reidel), 393.

Weaver, T. A., Zimmerman, G. B., and Woosley, S. E. 197S, *ApJ*, 225, 1021.

Weisberg, J. M., Romani, R. W.. and Taylor, J. H. 1989, *ApJ*, 347, 1030.



8 $M_\odot$ progenitor
10 AU
5 AU
3 AU
0
0.02
0.04
0.06
0.08
0.1
Probability of retention
0
20
40
60
80
100
Kick velocity (km/s)